Cover sheet:

Title: Dendrochronology

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The Encyclopedia of Geoarchaeology

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An A level entry (ca. 9000 words) on: Dendrochronology

DENDROCHRONOLOGY

Synonym: tree-ring dating

1.0 Definition

The word dendrochronology comprises three parts: dendron (tree), chronos (time) and ology (study of), and is defined as *'the science of dating tree rings'* (Kaennel and Schweingruber, 1995, 65). It is a dating technique that employs records of annual growth increments in trees to establish the calendar age of wood samples taken from living trees or from wood that has been utilised by humans. Dendrochronology is an absolute dating technique.

2.0 History

Interest in tree growth and the rings produced by this phenomenon has its origin in 15th century A.D. and possibly before. Leonardo da Vinci is often cited as the first notable scientist not only to write about tree growth, but also to speculate that tree rings and environmental parameters (rainfall) in the growing season might be linked (Schweingruber, 1983; Speer, 2010). In the 17th century, the invention of the microscope paved the way for wood anatomical studies, and by the mid-18th century, an understanding of tree-ring development had emerged from the work of Theodor Hartig and others (Schweingruber, 1983). It was not until the early 20th century that the principle of cross-dating was fully established and consistently applied by Andrew Ellicott Douglass (1867-1962), who is universally acknowledged as the *'father of dendrochronology'* (Schweingruber, 1983: 257). Douglass, and a team of co-workers, applied the newly emerging technique of dendrochronology to date archaeological sites in the American South-west. In 1923 the National Geographic Society sponsored a 'Beam Expedition' (Nash, 1999), which led to sampling of numerous timbers and the establishment of the first long tree-ring chronology back to A.D. 1280, as well as a 585-year floating chronology (Schweingruber, 1983). Douglass founded the first laboratory dedicated to dendrochronological research in 1937, the Laboratory of Tree Ring Research (Tuscon, Arizona), which has remained a centre of excellence in teaching and research, and has contributed significantly, although not in isolation, to the current large global network of tree-ring laboratories (Grissino-Meyer 2014).

Since the early twentieth century, dendrochronologists have produced records of absolutely-dated tree-ring patterns, tree-ring chronologies, stretching further and further back in time. In North America, two key species in chronology development have been the giant sequoia (*Sequoiadendron giganteum*) and bristlecone pine (*Pinus longeava*). The latter is particularly useful in dendrochronology, being very long-lived, as its Latin name suggests, with some individual trees living in excess of 5,000 years (Rocky Mountain Tree-Ring Research, 2013), with a continuous master chronology extending back 8,681 years by the early 1980s (Ferguson and Graybill, 1983). Their high altitude, in areas such as the White Mountains in California, makes bristlecone pines sensitive to temperature and precipitation. As a result, this species has been important in the development of long climate reconstructions (Scuderi, 1993; Woodhouse et al, 2011), in determining the global effects of volcanic eruptions on ecosystems (LaMarche and Hirschboeck, 1984), and in calibrating the radiocarbon timescale (Walker, 2005, 32-33).

In western Europe, a key species for dendrochronology is oak (*Quercus patrea* and *Q. robur*) due to its consistent growth patterns, rarely with missing or false rings, and its widespread occurrence both in natural environments and those associated with human activity, e.g. building timbers. Work began on producing long oak chronologies in the 1960s and 1970s, mainly in Germany and Ireland, but it was not until the early 1980s that the first long European oak chronologies were finalised (Pilcher et al, 1984; Baillie, 1995). A large network of local and regional chronologies has now been developed, providing the basis for routine dating of archaeological timbers (Haneca et al, 2009), as well as application in climate and other reconstructions (Rinne et al, 2013). Oak is a much shorter-lived species than bristlecone pine, so chronology building in western Europe has been based on cross-dating of many samples from living trees, buildings, and peat bogs, with ring-width patterns rarely exceeding 200 years.

Tree-ring chronologies now stretch back into the last ice age using trees that have grown in areas less influenced by the immediate effects of ice advances. German oak chronologies now cover the Holocene (Becker, 1993), and have been extended back into the last glacial period using a floating Preboreal Pine Chronology of previously unknown age (Spurk et al, 1998; Friedrich et al, 1999). This dating is based on dendrochronological cross-matching (see section 6.0) and on radiocarbon wiggle-matching (Baillie, 1995: 69-72). Although absolute dating cannot at present be guaranteed, sites from southern and central Europe have produced tree-ring records that date to around 14,300 years BP (Kaiser et al, 2012). **A BP date indicates years "before present," where the present is set at A.D. 1950 as the baseline standard for radiocarbon dating**. Future sampling in these geographical areas and the extension of chronologies may well lead to an absolute late-glacial growth record with significant implications for advancements in radiocarbon calibration and for improved understanding of past climate change.

In the southern hemisphere, there are also significant subfossil (**the preserved remains of a living organism that has undergone limited physical and chemical change**) tree-ring records forming floating chronologies potentially as far back as 45,000 – 25,000 years BP (Turney et al, 2010). These have been created following the sampling of subfossil Kauri (*Agathis australis*) buried in bogs in New Zealand. This long-lived species produces annual tree-rings that have a marked sensitivity to climate (Hogg et al, 2012). Turney et al (2010) highlight the possibility that further 'harvesting' of these trees and associated sampling for dendrochronology could have significant implications for radiocarbon calibration (see section 8.4), possibly as far back as 60,000 BP.

Long tree-ring chronologies have now been developed across the globe, with their extent only limited by the availability of wood of appropriate age. Dendrochronology has developed in mid-latitude areas, where tree growth is governed by seasonal weather patterns that produce distinct annual growth increments. Lack of distinct seasonality in the tropics initially made dendrochronology challenging (Worbes, 2002), but ring-width and isotopic measurements have isolated annual growth responses permitting the identification of annual signals in wood, and assessments of species suitability for dendrochronology and chronology building. Tropical dendrochronology is now an important emerging area within the subject (cf Robertson et al, 2004; Wils et al, 2011; De Ridder et al, 2013).

Two major traditions emerged in dendrochronology during the twentieth century which have been key to its growth: the North American tradition (with notable academics who continued the work of Douglass, including Schulman, Smiley, Hawley, Giddings, Haury and Fritts); and the European tradition, led amongst others by Huber, Liese, Becker, Eckstein, Schweingruber and Baillie. Dendrochronologists now comprise a global community brought together by similar research interests, international training, research collaborations, and conferences. Tree-ring analyses have a wide range of applications (see section 8) which are reflected in a vast array of journals in which dendrochronological research is now published, although the subject's roots and traditions are still clearly evident in the two main tree-ring specific journals and in the regular regional meetings held in both North America and Europe (Table 1). Tree-ring research is now well-established or becoming established in other areas, notably South Americas, Africa, and throughout Asia, as exemplified for instance by the growth of new organisations such as the Asian Dendrochronology Association (ADA).

Type	Name / details
International Conferences	International Conference on Dendrochronology (ICD or World Dendro) - 9th held in Melbourne, Australia, 13-17 January, 2014) Eurodendro AmeriDendro / The Association of American Geographers (AAG) Asian Dendrochronology Association (ADA)
Specialist meetings	Tree Rings in Archaeology, Climatology and Ecology (TRACE)
Dendroecological fieldweeks	N America, Europe, Asia
Specialist courses / workshops	Laboratory of Tree Ring Research Summer School (US) Wood Anatomy and Tree Ring Ecology (Switzerland) International Workshop of Tropical Dendrochronology (Brazil)
Databases	International Tree Ring Data Bank (ITRDB) The Bibliography of Dendrochronology (see Grissino-Meyer 2014)
Journals	Tree-Ring Research (formerly Tree-Ring Bulletin – N American) Dendrochronologia (European)

Table 1. Examples of current dendrochronology-specific conferences, meetings, workshops, courses and resources.

For extended coverage of the history of dendrochronology see Schweingruber (1983, 255-261), Baillie (1995), Nash (1999), and Speer (2010, 28-42).

3.0 Field sampling

Samples for dendrochronological analysis can emanate from a number of sources, including timbers that form part of standing buildings, wood from archaeological sites, trees preserved in peat bogs or other natural environments, and from living trees. A general rule at the outset of all tree-ring projects is to ensure that written permission is gained for sample retrieval from appropriate land or property owners.

3.1 Standing Buildings

Dendrochronology has dealt primarily with dating wood from standing buildings. Some of these may be private homes or public buildings, but many can be under renovation or in varying states of disrepair. It is therefore imperative that insurance is sought, and safe access is carefully considered, and that all relevant health and safety procedures are followed at all times (English Heritage, 1998). Initially a trained dendrochronologist should make a building assessment to judge suitability for tree-ring dating. This should include establishing the number of building phases present, type of wood used, presence of sapwood and bark, whether there are sufficient rings, and whether there is evidence of seasoning or timber re-use (English Heritage, 1998).

Samples (c 50-150 mm thick) can be taken using a hand or chain saw, but when such access is unavailable, timbers are cored *in situ* using a powered coring device. This consists of a hollow metal tube sharpened at one end (with saw teeth) which is attached to an electric drill (see Figure 1). Core removal is a skilled operation that aims to extract a cylinder of wood parallel to the medullary rays of the timber, ensuring tree rings are sampled at right angles to their original growth positions, with a goal to sample the maximum number of rings. Training is highly recommended from an experienced dendrochronologist to avoid unnecessary damage to buildings, and to avoid problems such as core overheating.

Figure 1. Sampling a roof timber (rafter), Salisbury Cathedral, UK (Image: J. Lageard).

3.2 Archaeological & natural environment sites

In archaeological and natural environment sites, sampling wood for tree ring analysis should follow the good practice outlined for standing buildings, but there are other important considerations.

Field locations should be carefully recorded and can also be contextualized within geomorphological maps. Disc samples from trunk sections should be cut at right angles to the bark, ensuring later ring measurements are not distorted. Research focussing on subfossil wood can involve techniques other than dendrochronology, and it is therefore prudent to consider the collection of samples other than wood concurrently, for example adjacent peat or other sedimentary deposits for the purpose of pollen analysis (cf Lageard and Ryan, 2013).

Archaeological sites frequently contain only small quantities of wood, often unsuitable for tree ring dating (e.g. Timberlake and Prag, 2005). At some sites, however, impeded drainage can lead to the preservation of large quantities of timber. Preparation of land for new housing at Kingsley Fields (Cheshire, UK) led to the discovery of a significant Roman industrial site, focussing on salt production. A total of 355 oak structural timbers were recovered and recorded, including those comprising a substantial wood-lined brine tank. In commercial archaeology it is rarely possible to date large wood assemblages in their entirety, and a spot dating approach is recommended whereby a small sample is analysed to better assess dating potential (English Heritage, 1998). At Kingsley Fields, seven samples were initially analysed in 2002, and a further 34 in 2004 in the post-excavation phase of the project (Tyers, 2012), providing an excellent basis for dating. A large quantity of timbers and their sub-samples raises important questions in terms of storage, conservation and later display, especially with limited local museum space and resources.

3.3 Living Trees

Deciding which trees to core depends on the nature of the research project. As a rule, dendrochronologists seek trees that demonstrate sensitive growth responses, as these contain more climatic information, and are more likely to cross-date (see section 6.0). Conversely, complacent growth (low variability among consecutive tree-ring parameters) should be avoided where possible.

The choice of sampling sites can be guided by this distinction, as trees located centrally within the geographical range of a species are more likely to produce complacent ring series, while trees growing in more marginal conditions at altitudinal or latitudinal limits generally exhibit sensitive growth responses (see section 8.5). Trees with sensitive ring series can also be found where other limiting factors are present, for instance pollution, geomorphological processes, and flooding (see sections 8.4, 8.6 and 8.7).

Particularly where specific phenomena such as flooding or pollution are being studied, it is important to establish a secondary field site (control site) where trees of the same species are not being influenced by the variable under investigation. The use of control sites is exemplified by Pelfini et al (2007) in a study of ice movement reflected in larch (*Larix decidua*) growing in debris on top of a small glacier in the western Italian Alps, and also in a study of water table fluctuations caused by solution mining in Cheshire, UK (Lageard and Drew, 2008).

Once a field site has been selected, it is important to collect a representative sample of the trees present. There are a number of different approaches that can be employed; two of the most widely used techniques employed are defining a specific sampling area and sampling along a transect. The former is often utilised when investigating stand dynamics, and the latter in studies involving ecological gradients of elevation, moisture, temperature, or pollution (Watmough, 1999; Lageard et al, 2008).

The approach to coring an individual tree depends largely on the nature of the research project. For example if the tree is growing on a slope, the force of gravity and the weight of the tree means the trunk will start to lean downslope. As long as the tree remains securely rooted, it will compensate for this downslope force by twisting the base of the trunk to allow the upper part of the trunk to grow vertically (sabre or geotopic growth). In conifers, such compensation causes the formation of compression wood (larger rings with thicker individual cell walls) on the downslope side of the tree. In hardwoods, the larger rings caused by a similar compensation, tension wood, develop on the upslope side. So if the research aims to date the year in which a slope became unstable, then trees should be sampled from either an upslope or a downslope direction. If, however, the research is trying to understand tree response to meteorological variables, coring parallel to the contour is advisable.

Powered corers can be used, but these are cumbersome, intrusive and potentially dangerous (Speer, 2010, 77-78), so it is more usual to employ a manual Pressler-type increment borer (lengths 100-1000 mm; diameters normally 5 or 12 mm) to retrieve a cylindrical core from the tree (see Figure 2). If properly maintained, borers may take several hundred cores during their lifetime.

Figure 2. Extracting a 5mm core from a cedar tree (*Cedrus libani*) in Morocco (Image: J. Lageard).

When coring, careful consideration should be given to a range of issues, including: sampling height (Brown 2007); avoiding branches or injuries; aiming for the pith; the number of cores per tree; the number of cores per sample site (Speer, 2010, 176); engaging the borer; and knowing when to stop coring to avoid borer loss. For more extensive advice on borer usage and increment core retrieval, see Grissino-Meyer (2003), Speer (2010, 77-87), and Haglöf (2014). There is little research that investigates tree mortality resulting from increment boring, although Wunder et al (2011) support general impressions of minimal impacts.

3.4 Waterlogged wood

Waterlogged wood can provide key dating control at archaeological sites, but mishandling can lead to sample deterioration and loss. As a consequence, guidelines (English Heritage, 2010) have been made available to assist archaeologists. Waterlogged wood is often by its nature very fragile, so great care should be exercised to prevent damage to samples. In particular, attention should be given to the preservation of sapwood and/or bark if present, as these can be crucial in producing precise felling or mortality dates. Increment cores and V-shaped wedges can also be taken where wood is being conserved as part of archaeological investigations (cf Bridge, 2011), but coring is problematic when weaker sapwood is present (English Heritage, 2010). In many cases, samples can be sawn by hand, but larger timbers may require the use of a chainsaw. Ideally, an experienced dendrochronologist or wood technologist would be involved in collecting samples as part of archaeological investigations and to advise on the suitability of samples for tree-ring dating (English Heritage, 2010).

4.0 Laboratory preparation

Increment cores should be processed ideally at the end of each field day. If left too long in enclosed spaces, cores can become mouldy, causing problems particularly if dendrochemistry is being investigated. Processing can involve sticking cores down with wood glue onto grooved wooden channels, ensuring that the rings are correctly oriented, as in their growth positions within the tree. Alternatively, in dendrochemical studies, cores can be held in place on the wooden channels using string or elastic bands.

Increment cores and robust samples can be left to air dry. Once dry, samples are sanded in order to clearly differentiate wood structure, particularly ring boundaries, to facilitate subsequent ring-width measurements. Because saw dust is carcinogenic, sanding should occur in well-ventilated facilities, where dust extraction systems are in operation. Powered sanders, with vibrating plates or rotating belts, are best employed using progressively finer sandpaper (Speer, 2010, 92-95).

Waterlogged archaeological samples can be soaked in or sprayed with PEG (polyethylene glycol) in order to preserve the integrity of the wood structure, as demonstrated in the conservation of the Tudor battleship Mary Rose and as a precursor to freeze drying smaller samples before measurement (Babiński, 2011). Wet wood samples are sometimes prepared using a scalpel or a sharp blade in order to clearly differentiate wood structure (Nayling and Susperregi, in press).

5.0 Measurement

Once wood samples have been collected and prepared, patterns of tree ring-widths or tree-ring series are measured. This process normally deals with rings starting from the oldest, ideally from the centre of the tree or pith, and finishing with the most recently formed, located immediately underneath the bark of living trees.

Records of ring-width patterns can be made using the skeleton plot method traditionally employed in North America (Schweingruber, 1983, 47-50; Cook and Kairiukstis, 1990, 43-44; Speer, 2010, 96-100). This technique is still widely employed today, and is particularly useful as a training tool (Sheppard, 2014), but ring-width measurements are now more frequently made using computer-based systems capable of an accuracy of 0.01 mm that employ specialised software, measuring stages, and binocular microscopes (Tyers, 1999; Speer, 2010, 102-103). Standard practice is to make consecutive ring-width measurements along at least two radii per sample. Once verified by cross-matching (see section 6.0), these are combined to make a sample mean.

Other measurement systems utilise high resolution flat-bed scanners to produce digital images which can then be manipulated using specialist software such as Windendro (Regent Instruments Inc., 2014) to produce ring-width measurements or to assess other parameters such as blue light reflectance (McCarroll et al, 2002).

Where sub-sampling of wood and preparation by sanding is impossible, such as for a valuable musical instrument, more sophisticated measuring techniques have been developed based on technique such as computer tomography (CT). Bill et al (2012) tested scanners used for medical and industrial purposes on air-dried archaeological oak samples and found that CT-scanning was as effective in dating archaeological objects as using conventional techniques, although more time consuming. Bernabei et al, (2010) successfully employed a 'Video Time Table', a portable measuring device and high-resolution video camera (VIAS, 2005) to assist in the dating of stringed instruments from the Cherubini Conservatory collection in Florence, Italy. This system also has the advantages of being non-invasive and deployable on site with minimal disturbance to museums or curators. Similar success was reported by Okochi et al (2007), who clearly demonstrated that an X-ray CT method could be used for the non-destructive measurement of ring-widths from wooden artefacts made of ring-porous Japanese oak (*Quercus mongolica*) and diffuse-porous Japanese beech (*Fagus crenata*).

Measurements of tree ring variables other than ring-width are now common in dendrochronological research. Dendrochemistry (see section 8.4), for example, can be employed to monitor historical changes in trace metal deposition. Once ring-width patterns are synchronised using standard dendrochronological techniques, cores can then be sub-sampled. These wood samples can then be digested in acid, and the resultant solutions filtered and analysed using techniques such as inductively coupled mass spectrometry (ICP) (Watmough, 1999; Lageard et al, 2008). These additional analyses are costly in terms of time, money, and facilities. Tree-ring density has been identified as a surrogate for summer temperatures, hence is widely used in climatic reconstructions (see section 8.5). Density data can require complex sample preparation and costly measuring equipment (Schwiengruber, 1983: 64-71), but image analysis and blue light reflectance is now thought to be a low cost surrogate for ring density (McCarroll et al, 2002).

A rapidly expanding area within dendrochronology is the use of the isotopic composition of wood to reconstruct past climate. Physiological processes governing, for instance, oxygen isotope composition ($\delta^{18}O$) in wood are now generally well understood (McCarroll and Loader, 2004), and the widely acknowledged correlation between wood $\delta^{18}O$ and precipitation has driven reconstructions as far back as AD 1697 (Rinne et al, 2013).

6.0 Cross-dating & Chronology building

Tree-ring series from wood samples thought to have grown contemporaneously are compared using a technique known as cross-dating, sometimes also referred to as cross-matching. This is the procedure '*for matching variations in ring-width or other ring characteristics among several tree ring series, allowing the identification of the exact year in which each tree ring was formed…'* (Kaennel and Schweingruber, 1995, 81).

Matching tree-ring series can be achieved manually using skeleton plots (see section 5.0) or by comparing ring-widths plotted on a semi-logarithmic scale. Both methods place emphasis on narrow rings to aid comparisons. More frequently due to the volume of data in modern research, mean ring-width measurements from individual trees or timbers are compared using specialist cross-matching software such as COFECHA (Holmes, 1983; Speer, 2010, 115-133) or DENDRO (Tyers, 1999). Cross-matching software contain routines that calculate statistically the strength of correlation between two ring-width series at a series of consecutive positions at which the two data sets could overlap. For instance, DENDRO utilises t-value calculations based on routines published by Baillie and Pilcher (1973) and Munro (1983) to highlight positions where the two ring series might match. If the t-values exceed specified criteria, for example $t > 3.5$, they are listed and form the basis for checking the reliability of correlations. Cross-matching between two samples should always be verified by visual comparison of ring-width plots, as relatively high t-values (e.g. $t \geq 6.0$) can give spurious results.

Once exact contemporaneity between samples is established, sample means can be combined to produce an averaged tree-ring record or a tree-ring chronology. Chronologies are produced for living trees in a specific geographical or ecologically defined area, and can be assigned calendar (absolute) ages if careful note is made of the sampling dates of living trees. Chronologies from living trees can then be extended further back in time using wood that has been preserved in buildings or within the natural environment (e.g. anaerobic peat deposits). Tree ring series from older sources of wood can be cross-dated with younger absolutely-dated records, extending the absolute chronology of tree growth further back in time using the bridging technique illustrated in Figure 3. Tree-ring chronologies are normally made from wood samples of a single species. They can be created using several different parameters such as ring-width, maximum ring density, vessel size, or isotopic composition.

Figure 3. A visual representation of how tree-ring samples are cross-dated using the bridging technique (Reproduced from Schweingruber 1983, 51 with permission – NEED TO SEEK!).

Once a chronology has been built, further statistical manipulation is possible, such as the calculation of its expressed population signal (EPS), which measures the strength of common variability amongst its component records, and standardization, which maintains low-frequency variability within the data whilst removing age-related growth trends (Speer, 2010, 141-142). Both EPS and standardization are considered essential in climate-related studies (see section 8.4).

7.0 Establishing a dendrodate

Over the last few decades the work of dendrochronologists has been instrumental in creating a large geographical network of master chronologies largely based on ring-width measurements (Haneca et al, 2009). Master chronologies can then be used to date wood samples from natural and built environments using the software outlined in section 6.0 (as illustrated in Figure 4). This process seems straightforward, but there are a number of factors including minimum sample requirements (see section 3.0), complacent growth, and irregular growth patterns (Cherubini et al, 2013) that can obviate a dendrodate.

Figure 4. A schematic representation of the process leading to a dendro or match date (From Baillie 1995, 17) with permission – NEED TO SEEK!).

Where an exact calendar age is assigned to a tree ring series, different dating scenarios can arise, providing important distinctions in archaeological and other interpretations. The presence of bark can provide an exact year or sometimes even season in which felling or mortality occurred (Hillam et al, 1990). If bark is lacking but some sapwood rings are present, an estimated felling date or mortality date can be calculated (English Heritage, 1998). Samples lacking bark and sapwood can only provide a *terminus post quem* (date after which death occurred).

8.0 Applications

Tree ring chronologies facilitate dating of wood sampled in natural and anthropogenic contexts. But dendrochronology has much more to offer than the calendrical dating of building timbers. Dendrochronology has now been applied in a number of subfields, from tracing movements of timber (section 8.2) to studying the timing and impacts of past volcanic eruptions (section 8.9).

8.1 Archaeological Dating (Dendroarchaeology)

Dendrochronology is a widely used and accurate dating tool employed as an integral part of archaeological investigations (Baillie, 1982). In the American Southwest, dating both charcoal samples and beams used in building construction have provided a detailed understanding of the development of native Pueblo cultures (Nash, 1999; Speer, 2010). Recent developments in archaeological dating include chronology development from salvaged river logs (Dick et al, 2014).

Haneca et al (2009) list some important European archaeological sites that have both benefitted from, and been instrumental in the development of routine tree-ring dating. These include the Viking settlement of Haithabu (Hedeby, Germany – Eckstein, 1969; Eckstein and Wrobel, 2007), prehistoric lake shore settlements (pile dwellings) in the area surrounding the Alps (Billamboz, 1996; 2008) and the Neolithic Sweet Track in the UK dated to 3807 / 3806 BC (Hillam et al, 1990). Haneca et al (2009) also note the success of routine dating for archaeological samples based on a dense network of chronologies that have developed in northern and western Europe following the development of long chronologies and the proliferation of dendrochronology laboratories, particularly since the 1990s. Tree-ring dating remains difficult in some areas, particularly to the southeast of the Alps (Italy, Slovenia, Austria) due to a lack of prehistoric chronologies (Haneca et al, 2009).

Widespread dating of both vernacular and more prestigious buildings (for example, castles and cathedrals) during the historic period has revealed progression in architectural styles over time, unknown construction or repair phases, and the stockpiling of wood for prestigious building projects (Hoffsummer, 2002; Hillam and Groves, 1996; Miles, 2006).

Exciting developments related to the use of dendrochronology in archaeological dating are the dating and provenancing of shipwrecks (cf Cufar et al, 2014; Nayling and Susperregi in press; see section 8.2) and the reconstruction of past forest management practices (section 8.10).

8.2 Sourcing timber (Dendroprovenancing)

Dendrochronology in Europe has developed regionally with chronologies being constructed and wood dated at local and wider regional levels. As the geographical coverage of chronologies developed, cross-matching and dating wood was possible over greater distances, but there were still limits to this based on tree growth responses governed by regional climates and environmental conditions. For example, cross-matching is often possible between England and Ireland, but not between Ireland and Germany or between England and Poland. Haneca et al (2009, 6) capture the essence of these relationships in their definition of dendroprovenancing:

'Trees experiencing similar growth conditions are expected to develop a comparable ring-width pattern. This is one of the basic principles of dendrochronology. Trees from distant geographical locations will develop growth ring patterns with different characteristics, driven by discrepancies in the local climate and site conditions. This supports the assumption that a tree-ring pattern contains information related to the location at which the tree grew. Comparison of individual tree-ring series with chronologies that reflect the average growth conditions for specific regions allows the sourcing of the origin of the timber, i.e., dendro-provenancing.'

The proliferation of European oak chronologies in the 1980s opened up the possibility of unravelling significant problems previously encountered in tree-ring dating. Cases in point were the art-historical oak chronologies created in the 1970s. Medieval paintings were often made on thin oak boards or panels. Attempts to date these by measuring oak ring-width series and comparing them to oak chronologies constructed from local timber sources often failed. It was suspected that the oak boards may have come from more distant locations (Baillie, 1995; Eckstein and Wrobel, 2007). Creation of a Gdańsk-Pomerania chronology by Wazny (Eckstein et al, 1986) was key to dating wood used in creating Dutch paintings and also wooden artefacts from Lübeck Cathedral, separating German timber from Baltic timber sources (Eckstein and Wrobel, 2007). The medieval Baltic timber trade has also been revealed in imports of wood used for construction purposes in the British Isles, as at Stirling Castle, Scotland (Crone and Fawcett, 1995; Mills and Crone, 2012). Art-historical oak wood in Europe is now routinely dated using Polish and Baltic reference chronologies (Haneca et al, 2005).

Perhaps the most often quoted example of dendroprovenancing is the case of Skuldelev Ships which were excavated in a Danish fjord between AD 1958 and 1962. These included warship, trading and fishing vessels that were clearly of Viking age in their construction, yet their oak tree-ring series did not cross-match against any German or Scandinavian chronologies. Some aspects of their design hinted at a possible British origin of the wood, and subsequent comparisons with English and Irish chronologies showed highest correlations with a chronology constructed from trees that had grown in the Dublin area (Ireland). This led to the conclusion that Vikings who had settled in Ireland constructed the ships from Irish oak around AD 1060, before sailing them back to Denmark (Bonde and Crumlin-Pedersen, 1990; Baillie, 1995).

Tree-ring chronologies now form a dense geographical coverage, particularly in northern Europe, affording the possibilities of high-resolution dendroprovenancing (e.g. Daly and Nymoen, 2008). Such studies may, however, suggest more than one possible timber origin, so the results of attempted dendroprovenancing are not always easily interpreted (Bridge, 2011; 2012). Nevertheless, tree-ring research focussing on dendroprovenancing is an increasingly important area within dendrochronology.

Sources of wood transported by rafting on rivers in central and northern Europe (for charcoal used in the production of iron) have been traced by Grabner et al (2004). In southern Germany, the altitudinal sensitivity of growth in spruce (*Picea abies*) and fir (*Abies alba*) has permitted the provenancing of rafted logs to specific mountain areas (Dittmar et al, 2012). Dendroprovenancing can play a valuable role in the evaluation of the relative integrity of historic buildings (Sass-Klaassen et al, 2008). In addition to ring-width measurement, elemental and isotopic analyses of tree-rings have added important new dimensions in dendroprovenancing (Durand et al, 1999; Reynolds et al, 2009; Kagawa and Leavitt, 2010).

8.3 Dendroecology

Dendroecology is a subfield of dendrochronology and encompasses all the other subfields that use dated tree rings to study ecological problems and the environment (Kaennel and Schweingruber, 1995). Examples of other subfields include dendrochemistry, dendroclimatology, dendrogeomorphology, dendrohydrology, dendroglaciology, dendrovolcanology, and a number of subfields that assist informed forest management – all covered in the sections below.

8.4 Pollution – air & soil (Dendrochemistry)

Dendrochemistry has been defined as *'...the use of tree rings as indicators of past chemical fluctuations in the environment.'* (Cutter and Guyette, 1993, 612). It has been widely employed in attempts to reconstruct pollution histories, and also in the calibration of the radiocarbon (^{14}C) timescale.

Pollution directly resulting from human activities is known to have a detrimental impact on trees causing tree mortality, such as for those in close proximity to industrial plants (Schweingruber, 1996). The key question is whether dendrochronology can be used to accurately reconstruct annual fluctuations in pollutants.

There are a number of issues and potential problems in dendrochemical research, including: species suitability; pollution pathways (leaves, needles, bark or roots); the effects of soil acidity on elemental uptake (cf Guyette et al, 1991); elements essential or non-essential for growth; radial translocation within wood (cf. Watmough and Hutchinson, 2002); tree age; variations in elemental concentrations in trees sampled close together, and potential chemical contamination of increment cores. These lead Smith and Shortle (1996, 633) to write *'...radial trends of chemical data are not good places to "go fishing" for research topics.'*

Nevertheless, if careful consideration is given to potential shortfalls in designing research projects (Watmough, 1999), successful pollution reconstructions are thought to be possible (Lageard et al, 2008) which can shed light on the scale of human impacts on the environment in industrial archaeology. Figure 5 shows dendrochemical records obtained from Scots pine (*Pinus sylvestris*) growing adjacent to and at 9 km distant from a lead smelter in Derbyshire, UK. These records mirrored anticipated pollution trends based on industrial output and on increasing use of mitigation technologies. Other studies have concluded that accurate pollution reconstructions were impossible for combinations of the factors listed above (e.g. Patrick and Farmer 2006).

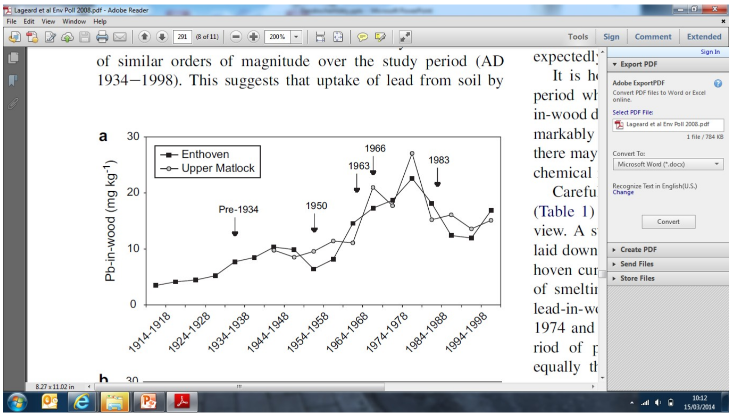

Figure 5. Dendrochemical records from Scots pine (*Pinus sylvestris)* sampled at two sites located 9 km apart in the Peak District, Derbyshire, UK. (From Lageard, et al 2008). NEED TO SEEK PERMISSION - Elsevier

Measurements of isotopic variations in wood that has been used in the construction of long absolutely–dated tree-ring chronologies in Europe and North America have also provided records of natural variations in the production of radiocarbon (^{14}C) that are now routinely applied in the calibration of radiocarbon dates (Walker, 2005, 32-36).

8.5 Climate reconstruction (Dendroclimatology)

Climate is *'...one of the main controlling factors of most tree-ring growth across all spatial and temporal scales'* (Speer, 2010, 174). There are a number of approaches that have been adopted in order to reconstruct past climate and its effects on trees and their spatial distributions. These include calibrating growth responses with meteorological data, and studying growth responses or the presence / absence of trees related to present-day latitudinal and altitudinal growth limits.

Dendroclimatic reconstructions seek to establish a link between specific climatic variables and tree growth, usually through statistical comparisons of tree-ring and meteorological data. Generally standard field and laboratory methods are employed, but careful attention is required for climatically-sensitive site selection, tree age, number of samples (Speer, 2010), and the need for removal of age-related growth trends (standardization). The climate response of trees is achieved using a correlation matrix or response function analysis, to compare the master chronology with monthly climate data to identify months or seasons that correlate with ring-width data. Calibration then occurs as a transfer function (Fritts, 1976), describing the relationship between the tree rings and climate variables using linear regression analysis. Transfer function coefficients are used to transform or rescale the tree ring sequence into a new sequence of meteorological estimates that can be extended back in time for the whole length of the tree-ring sequence (Schweingruber, 1983). The final stage is verification, when the validity of the model is tested by comparing reconstructed climatic data with real data that have not been used in the calibration.

Examples of dendroclimatic reconstructions based on different tree-ring parameters include Briffa et al (2001) who reconstructed summer temperatures for the northern boreal forest over the previous 600 years based on ring density, and Rinne et al (2013) who utilised $\delta^{18}O$ isotope measurements to reconstruct precipitation back to AD 1697.

Climatic reconstructions can also be achieved using routine dendrochronological techniques. For example, Shumilov et al (2007) studied Juniper (*Juniperus siberica*) on the Kola Peninsula, Russia, using ring-width analyses, establishing a 676 year chronology. This record correlated well with known periods reduced solar radiation (Sporer, Maunder and Dalton minima) and associated decreases in hemispheric temperatures. Subfossil larch (*Larix sibirica*) has also been used in latitudinal reconstruction of climatically-induced latitudinal fluctuations in the northern boreal tree line (Hantemirov and Shiyatov, 2002), and the altitudinal limit of stone pine (*Pinus cembra*) was reconstructed by Nicolussi et al (2005) in the Austrian Alps, during the last c 9,000 years using living trees and subfossil samples retrieved from till in glacier forefields. Neuwirth et al (2007) employed the more traditional pointer year approach (Schweingruber et al, 1990) in conjunction with GIS to identify spatial patterns in positive and negative growth anomalies evident in 377 ring-width chronologies from central Europe. ~~(~~**Ppointer years are cross-dated years in which the majority of trees investigated have responded simultaneously to events such as the Europe-wide drought experienced in A.D. 1976).**

As climatic reconstructions have become more widespread, it is now possible to map the effects of specific climatic variables across regions and continents, dendroclimatological networks (cf Fritts 1976). Esper et al (2009) utilised 53 ring-width and 31 maximum latewood density chronologies across northern Eurasia to establish an east-west climatic gradient, and a correlation between larch (*L. decidua*) and temperature. D'Arrigo and Jacoby (1991) found links between El Niño and climate in the Southwestern USA. North Atlantic Oscillation sea surface temperature signatures are also apparent in tree-ring records of Scandinavian pine (*P. sylvestris*) chronologies (d'Arrigo et al, 1993).

The impacts of major climatic events on human populations have been clarified through tree-ring based reconstructions (Jacoby et al, 1999; Stahle et al, 2000). Chronology building itself has also produced periods where few dated samples are available (Baillie, 1995), thought originally to be artefacts of sampling strategies. These may be genuine 'gaps' related to climatic downturns or other factors such as disease that have impacted human populations (Brown and Baillie, 2012).

Application of dendrochronology to climate has been *'One of the most publically debated applications of dendrochronology'* (Speer 2010: 174). This statement referred primarily to the controversial 'hockey stick' multi-proxy climate reconstruction of Mann et al (1998) that provided early scientific evidence in support of global warming exacerbated by human industrial activity (IPCC, 2007). Dendroclimatology and its statistical methods again came under international scrutiny in 2009 with 'Climategate' (Carrington, 2011).

Recent dendroclimatological research has identified hydroclimatic events of great magnitude and duration in central Europe that may have had significant past political consequences. Büntgen et al (2011) argue that these should serve as historical justification for expenditure re current projected climate change.

8.6 Slope instability (Dendrogeomorphology)

This subfield of dendrochronology has been defined as *'The use of tree rings to date geological [sic geomorphological] processes that affect tree growth.'* (Speer, 2010, 219). Its significance in geoarchaeology is that it can help in developing an understanding of how natural processes can influence human activities, notably settlements, and how natural processes can also affect archaeological sites, particularly those that were abandoned and then colonized by trees. Schweingruber (1996, 272) noted that dendrochronology had rarely been considered in mountain forests where geomorphological processes are common, and stated that *'only dendrochronology is able to provide information about the frequency and extent of past events.'*

Trees react in a number of ways to the onset of slope instability or instability caused by other processes, for example advancing ice (dendroglaciology – section 8.8). Onset dates, years, or sometimes seasons can be identified from a variety of evidence preserved in tree ring records such as: the formation of reaction wood (section 3.3) in response to trees starting to lean; scars left following damage to the bark and cambium; root exposure; tree mortality, and tree establishment germination dates (**ecesis**).

Although the principles of dendrogeomorphology were established in the 1970s (Alestalo, 1971; Shroder, 1978), research in this area has only recently proliferated, benefitting from advances in dendrochronological techniques and in computer technology. For instance, Stoffel et al (2005) made detailed analyses of the impacts of rock falls in the Swiss Alps on European larch (*Larix decidua*). In addition to dendrochronological dating, they used GIS software to vizualize the spatial extent, as well as the timing of events. Such studies have important implications for reconstructing past mass movement activity and are key tools in hazard mapping and hazard mitigation. Similar research has been undertaken for different types of mass movement such as debris flows (Bollschweiler et al, 2007; Sorg et al, 2010).

Dendrogeomorphology also includes research dating lakeshore erosion (Fantucci, 2007), tectonic movements such as earthquakes (Jacoby et al, 1997) and the build-up of coarse wood debris (Campbell and Laroque, 2007).

8.7 Impact of water (Dendrohydrology)

'Dendrohydrology uses dated tree rings to study and date hydrologic phenomena, such as river flow, lake level changes and flooding history' (Kaennel and Schweingruber, 1995, 71). Trees growing in a variety of landscapes from upland to lowland can be affected by hydrological events. For instance, trees bordering streams and rivers can be uprooted by flood events, tilted as soils and banks are washed away or scarred by debris carried by flood water. Subfossil trees preserved in sediments marking old river courses in central Europe have been a key resource in building long master chronologies (Becker, 1993).

Dating scars and abrupt growth changes allows a temporal and spatial assessment of the disturbance regime. Zielonka et al (2008) reconstructed flood history in the Tatra Mountains, Poland, using cross-dated scars from trunks of Norway spruce (*Picea abies*). Flood events identified were compared to meteorological data, and although no one variable could be held responsible for all the flooding, the dendrochronological approach identified otherwise invisible flood events. Trees can also be defoliated during flooding, which can affect wood structure as demonstrated for young ring-porous ash trees (*Fraxinus Americana* , *F. pennsylvanica*) by Yanosky (1983). Erosion during flood events can cause sediment loss and root exposure, leading to growth reductions and tree destabilization and the formation of compression and tension wood. In riverbeds, undermined trees often lean in the direction of water flow. Sediment deposited by floods can lead to the growth of adventitious roots and shoots (the development of secondary cambium on older stems, branches and roots), both of which can be dated to establish timing of their response to flood events. As flows subside, trees germinate in locations protected from water flow, for example on the stream side of boulders. Riverbed trees can provide minimum ages since the last major flood event (Schweingruber, 1996, 133).

In colder climates ice can scar trees on river banks (Payette and Delwaide, 1991) and lakeshores. Research focussed on the latter has used combinations of ice scars and tension wood resulting from tree tilting by waves to reconstruct higher water levels and to make inferences about increased flooding events and climate change (Bégin, 2001). In more arid areas, tree-rings of bristlcone pine at lower elevations have been shown to be sensitive to the combined effects of precipitation and evapotranspiration. In a hydroclimatic reconstruction, Woodhouse et al (2011) were able to estimate water flow in the Arkansas River (USA) from AD 1275 – 2002.

Génova et al (2011) investigated small wooden 'canals' used to channel river flow and to drive machinery of the 16th Century Old Mint in Segovia, Spain. Dendrochronology was used to date timbers used in repairs following flood events and these data were compared to documentary records to confirm the timing of flood events, to assess their relative magnitude, and also to identify undocumented floods. Dean (1993), studying canyon terraces in Arizona, USA, successfully employed geological and archaeological analyses together with tree-ring dating to reconstruct landscape history.

Groundwater levels can have significant effects on trees. Although species demonstrate different tolerances to water in soil (cf Vreugdenhil et al, 2006), prolonged waterlogging will often lead to significant growth reductions and eventually tree mortality.

Peat bogs are naturally wet places, but during drier periods, they can be colonized by trees. Layers of mire-rooting woodland have been uncovered, usually during commercial peat extraction, and dendrochronological investigations have now produced absolutely-dated ring-width sequences that demonstrate distinct periods of germination and mortality during the Holocene associated with climate-driven hydrological variations on bog surfaces (cf Eckstein et al 2010). In coastal areas, often rich in archaeology, salt water incursions caused by post-glacial sea level rise have been responsible for woodland mortality of submerged coastal forests on the Dutch coast (Munaut, 1966), and of the inter-tidal woodland and associated Mesolithic and Neolithic archaeology of the Gwent Levels, south Wales (Bell et al, 2001).

Deliberate human interventions in the landscape can improve conditions for tree growth through drainage (Schulthess, 1990). Artificial aridity can conversely be detrimental to tree growth as exemplified for example, by solution mining. In the hydrogeological research documented by Lageard and Drew (2008), the growth responses of oak (*Q. robur*) were shown to be governed by water table variations resulting from brine pumping in the Cheshire saltfield (UK). Significant reductions in ring-widths could be related to the construction of brine processing sites in the 1920s, and precisely to the cessation of all pumping activities in AD 1977.

Figure 6. Surface depressions resulting from uncontrolled solution mining of salt and the collapse of underground cavities in Cheshire, UK: 6a – subsidence lake or 'flash'. 6b – a possible 'brine run' resulting from solution of salt beds at depths of c 30-40m. Such landscape features document hydrological change that can impact tree growth, whilst the latter can document the environmental impacts of industry

8.8 Impact of ice (Dendroglaciology)

Dendroglaciology is the use of tree ring series to date and to ascertain the extent of past glacier movements, defined by relic landscape features such as moraines and trimlines. This subfield has close affinities to dendroecology and dendrogeomorphology, as trees react to ice advances and retreats in forested areas by: being scarred or killed by ice advances, tilted by ice advance and by colonizing glacier forefields on ice retreat. In Europe, the rate at which different species colonise freshly de-glaciated land (**ecesis**) has been studied in localities such as the Aletsch Glacier in Switzerland, where colonization by spruce (*Picea abies*) and larch (*L. decidua*) took on average 20 years, whereas stone pine (*Pinus cembra*) took 45-85 years (Schweingruber, 1983).

Classic dendroglaciological research has mapped the maximum extent of Little Ice Age outlet glaciers emanating from the Columbia Icefield in the Canadian Rockies (Luckman, 1988), and also reconstructed glacial mass balance (inputs and outputs to glacial systems), for example a 600-year reconstruction in the Austrian Tyrol (Nicolussi and Patzelt, 1996), and a 400-year reconstruction using hemlock (*Tsuga mertensiana*) for two glaciers on Vancouver Island, western Canada (Lewis and Smith, 2004). Further information on the history of, and techniques employed in dendroglaciology is available in Smith and Lewis (2007).

8.9 Volcanic impacts (Dendrovolcanology)

There are a number of ways in which volcanic eruptions / episodes can affect tree growth. Tree mortality can be caused by shock or heat waves, hydrological change (as volcanic sediments can case prolonged flooding) or through natural pollution ($S0_2$, fumaroles). Growth suppression can result from the proximity to lava flow causing tree tilting, scorched crowns, dust-reducing photosynthesis, responses to burial by volcanic sediments, and volcaniclastic sediment preventing germination. Volcanic impacts can conversely improve tree growth when the death of emergent trees leads to subsequent growth release in trees of the previously supressed understory. Fine volcanic ash, in contrast to coarser volcaniclastics, promotes rapid seed germination (Schweingruber, 1996).

Dendrochronology can therefore be used to study the environmental impacts of volcanism, and also to date specific events during the historic period when documentary evidence does not exist. For example, Yamaguichi et al (1990) dated the extrusion of 'Floating Island' lava flow to late A.D. 1799 or A.D. 1800 at Mt St Helens, USA using living trees, and Yadav (1992) reconstructed regional volcanism on the Kamchatka Peninsula, Russia. Jacoby et al 1999 demonstrated major human impacts on the Alaskan Inuit following the eruption of Laki in A.D. 1783.

Volcanic events can also be dated by sudden growth reductions preserved in timber, such as a beam from Wupatki, Arizona (USA), thought to date an eruption of Sunset Crater to A.D. 1064 (Smiley, 1958). Similar growth reductions can also appear within subfossil tree-ring series from prehistory. Contemporaneous narrow ring events, (NREs) found in bog oaks preserved in natural environments such as peat bogs throughout northern and western Europe, are thought to indicate long-term climatic cooling, so called ‘volcanic winters’, caused by the prolonged presence of volcanic aerosols in the atmosphere (Baillie, 1995). Chronologies based on ring density have also clearly demonstrated the climatic impacts of volcanism on summer temperatures during the historic period (Briffa, 2000).

Dendrovolcanology is, however, not without its controversy. Narrow rings in European bog oaks supported by the simultaneous appearance of frost rings in bristlecone pines (LaMarche and Hirschboeck, 1984) have provided an absolute date for the catastrophic Bronze Age eruption of the Greek Island of Santorini, 1628 B.C. (Baillie and Munro, 1988; Baillie, 1995). Problems occur when attempts are made to correlate a tree-ring date such as this with loosely-dated environmental evidence, for instance acidity layers preserved within ice cores (Baillie, 1991). The 1628 B.C. date continues to generate controversy (Zielinski and Germani, 1998), probably due amongst other things to emotive links to the legend of Atlantis. Similar debates have arisen concerning other notable prehistoric eruptions, such as Hekla 4 with a ~~-~~dendrodate of 1159 B.C., when scientists try to make links with other palaeoecological records loosely dated by radiocarbon, such as those obtained from **pollen analysis** (~~cf~~ Payne et al, 2013).

Volcanoes are not the only environmental mechanism capable of causing sudden climate change and prolonged growth reductions in trees. The A.D. 540 NRE has been linked to the effects of specific volcanoes, but the dating evidence (^{14}C) is inconclusive, and it is possible that a meteorite strike similar or greater than that experienced at Tunguska (Siberia) in A.D. 1908 could have caused significant disruption to the Earth’s atmosphere over a number of years (Baillie, 1995, 91-107).

8.10 Forest Management

Dendrochronologcal research has been used increasingly by foresters in the management of woodland resources, for instance in assessing the role of fire in the landscape (d~~D~~endropyrochronology), damage caused by insects (~~D~~endroentomology**)** and also changes in species composition. Humans are key agents of change in forests and woodlands, and as such dendrochronological reconstructions of the extent and composition of forested areas are of relevance to archaeology, particularly in understanding the evolution of cultural landscapes.

Schöne and Schweinguber (2001) used dendrochronological techniques to reconstruct the history of natural reforestation in the Inn Valley, Switzerland, since World War II following land abandonment in response to changing management practices and rural-urban migration. Such abandonment often results in reduced biodiversity, as highlighted in Sweden when traditional Medieval farming practices lapsed (Hayashida, 2005). In these abandoned landscapes older trees, originally retained for practical, cultural and aesthetic reasons, often remain concentrated around villages as relict features. Combinations of dendrochronological data and information gleaned from other sources such as forest management records (Müllerová et al, 2014) and livestock inventories (Genries et al, 2009), can be used to reconstruct land use history, and also to make informed choices regarding conservation management. There is also potential for similar dendrochronologically-informed reconstructions in former industrial landscapes, and in relict battlefield landscapes, for example in parts of the European Alps fought over in the First World War (Thompson, 2008). In the future, dendrochronology could play an important role in multi-proxy archaeo-environmental studies attempting to shed more precise light on significant military deforestations already apparent in palynological (Dumayne and Barber 1994; Dumayne-Peaty, 1998) and documentary research (Plusowski et al, 2011).

Trees can be affected by fire of both natural and human origin. Tree mortality will result if the bark and cambium are killed around the full circumference of the trunk, but some tree species, notably pines (Richardson, 2000; Lageard et al, 2000), have developed resistance to fire, and protect damaged areas of the trunk by producing callus tissue and forming a scar (Schweingruber 1983: 206). In fire-prone regions, a series of fires can burn into a tree leaving a set of overlapping scars and sometimes a large triangular scarred area at the base of the trunk known as a catface (Speer 2010: 197). In some species the impacts of fire may be more subtle and only noted by carefully documenting anomalous wood structure, for instance in black ash *Fraxinus nigra* (Kamesa et al, 2011). Scars can be sampled from living and dead trees by cutting discs or partial sections using a chainsaw (Anro and Sneck, 1973). Once prepared using standard techniques (section 4.0) these samples can be dated by dendrochronology to calendar years, seasons or even parts of seasons (as illustrated by Swetnam and Baisan, 1996). Records of fire scars in individual trees can be synchronised in fire history charts to document regional fires over prolonged periods (Swetnam et al, 1999) and the calculation of fire return intervals. The latter can be related to human interventions and the significance of fire as a management tool can be seen for instance, in its use by N~~n~~ative Americans to favour mast-producing trees such as oak, hickory, chestnut and walnut. These management practices are thought to have had a major impact on the distributions of present-day forest and grassland ecosystems of Eastern USA (Abrams and Nowacki, 2008). Dendrochronology now also provides the scientific basis for fire suppression policies in the USA that became prevalent in the later t~~T~~wentieth c~~C~~entury, as foresters and politicians struggled to combat the effects of fire on humans and their habitations (Speer, 2010).

9.0 Summary & future directions

Dendrochronology is a powerful absolute dating technique that has been employed in many research projects that can be linked directly or indirectly to geoarchaeology. The technique has its limitations in terms of suitability of tree species, suitability of sampling sites, and minimum sample requirements for computer-assisted cross-matching. That said, the technique has been applied in numerous environments, both natural and those affected by humans.

Traditionally dendrochronology has been applied in the dating of wood from archaeological sites and from standing buildings, but the technique has much wider application, and also potential. Of particular relevance to g~~G~~eoarchaeology is the use of dendroprovenancing that can reconstruct historic and potentially prehistoric movements of timber from forest source regions, reconstruction of past land use, industrial and pollution histories, and climatic reconstructions that can be used to assess climatic / environmental impacts on past and future human population.

Baillie (1995, 32) sums up the significance of the technique: *'The power of dendrochronology to date things precisely opens up a whole new window into the past…'*.

The utility and future directions of the technique~~ / subject area~~ are often discussed at conferences (Baillie, 2002; Sass-Klassen, 2002). Some important themes in this respect have included: the handling and storage of increasingly large quantities of data (Jansma et al, 2012); improving dendrochronological coverage, spatially and temporally; dendroprovenancing; the use of tree-rings as sources of environmental data; funding for academic and private laboratories; co-operation between dendrochronology and other disciplines, and also the need for dendrochronology to receive proper recognition as an interdisciplinary subject in academia.

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Cross references

Dating methods

Geomorphology

GIS

Mass movement

Paleoenvironmental reconstruction

Radiocarbon dating

Santorini

Volcanic events

Hydrology

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